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Numerical Analysis of Translational Vibration Reduction Response on Drilling Process Due to Additional Mass-Rubber Dynamic Vibration Absorber (MR-DVA)

Dika Andini Suryandari, Wiwiek Hendrowati*

Department of Mechanical Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia

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Abstract

Machining is an important part of the industry, one of which is the drilling process. The drilling process is utilized in the making of holes in a material. When the drill-bit touches the material, it causes a vibration that can affect the quality of the hole surface. Therefore, the analysis of the addition of MR-DVA with a natural frequency of 1,630.2 Hz on a workpiece Aluminium Alloy 7075-T6 as the main system is conducted. Simulations were carried out in the natural frequency range of 1,675 Hz – 1,680 Hz with various workpiece dimension ratios of 2/5, 3/5, 4/5, and 5/5, along with the different ratios of an MR-DVA placement between the clamp and hole of 1/4, 2/4, and 3/4. Based on the conducted simulation, it has been found that the MR-DVA with a mass ratio of 1/20 can dampen well. The largest reduction for a workpiece dimension ratio of 2/5 with an MR-DVA placement ratio of 1/4 is 92%. In contrast, the smallest reduction for a workpiece dimension ratio of 3/5 is 7.2%. These are because the damping area and the increase in the workpiece's dimensions ratio are inverses, affecting the workpiece area that touches the clamp.

Keywords: Drill, drilling, MR-DVA, reduction, vibration

1. Introduction

Metalworking is an important industry, especially in the manufacturing world. The machining tool most often encountered for metalworking is the drilling machine. When the drilling process takes place, and the drill bit begins to touch the workpiece's surface, vibrations from the operating motor are transmitted. This can affect the quality of the hole surface and the age of the components that make up the drill machine. The vibration of the drilling machine can be controlled by adding a Dynamic Vibration Absorber (DVA).

The use of dynamic vibration absorbers (DVA) in various conditions with different parameters has been done to create the best damper for each situation. Therefore, the development of DVA is still being developed today, according to an experimental study of self-tuning dynamic vibration absorber (DVA) on machining tools due to friction between the cutting tool and workpieces [1]. The result found an increase in machine effectiveness because DVA automatically adjusts the required damping to the milling machine's rotational speed, increasing the cut depth from 3 mm to 5 mm, and improving the cut surfaces' quality. As a result, the CPVA with 1400-2400 piezoelectric cantilever, which operates at a natural frequency of 20.61 rad/s with an amplitude of 0.3 and 0.35, can reduce vibrations up to 20.28% - 22.75% and generate electrical energy from 2.17×10^{-7} to 5.78×10^{-7} watts. A simulation to optimize the use of DVA in the form of a cantilever beam installed on drill bits for the boring process has been carried out [2]. The result obtained for the DVA stiffness of 200 kN/m can reduce optimally, characterized by low amplitude. Then, experiments and modeling on a prototype tuned mass damper to dampen the milling process were carried out [3]. The research found that DVA reduced up to 20 times the main system response without DVA and produced a better and smoother workpiece surface. Analysis of the use of Cantilever Piezoelectric Vibration (CPVA) to reduce the translational vibration of the main system has been carried out [4]. This simulation proves that CPVA can dampen up to 20.36% and produce 3.52×10^{-7} Watts of electrical power at its natural frequency.

An experimental study on adding a Translational Mass Vibration Absorber (TMVA) to a drilling machine has been carried out [5]. The result of this study shows that TMVA can reduce vibration in the drilling process and reduce the chattering effect on the surface of the hole due to the increasing effectiveness of the machine. The next study simulates adding a cantilever piezoelectric vibration absorber (CPVA) to dampen the multi-DoF system [6]. The result of this study shows that CPVA can reduce translational and rotational vibrations up to 98% and 67%, respectively. A study of the cantilever piezoelectric vibration

*Corresponding author. Email: wiwiek@me.its.ac.id.

absorber (CPVA) mechanism was optimized by adjusting the piezoelectric cantilever [7]. As a result, the CPVA with 1400-2400 piezoelectric cantilever, which operates at a natural frequency of 20.61 rad/s with an amplitude of 0.3 and 0.35, can reduce vibrations up to 20.28% - 22.75% and generate electrical energy from $2.17 \times 10^{-7}$to 5.78 $\times$ 10^{-7} watts. Simulation research has been conducted by designing a DVA that is installed to a boring bar to increase the lathe's effectiveness [8]. The outcome of this research is that the spring stiffness of natural rubber has the greatest reduction effect because it has the highest stable damping area. Simulation research on the optimization of DVA design using the genetic algorithm method for 5 degrees of freedom (DoF) of machining tools was conducted [9]. This simulation shows that the optimal use of DVA is when DVA is placed on the workpiece and cutting tools.

An experiment on passive dampers for the drilling process has been carried out [10]. Partial damping is a passive damping concept using small metal or ceramic particles or powders placed in a cavity with a high density. The result shows that passive dampers can reduce vibration caused by drill bits, reduce workpiece surface finish, and minimize the loss of static stiffness by applying passive dampers. A simulation on the optimization of damped DVA to withstand the reciprocal forces of the main system has been carried out [11]. The simulation found that the greater the ratio of DVA mass to the main system, the greater the damping area produced by the system. An experiment that finds the chatter frequency of the drilling process was conducted by varying the material from drill bits [12]. The results were obtained from the difference between the operating frequency and the chatter frequency in the drilling process, which is the chatter found within the observable frequency at 1,100 Hz. A Matlab simulation was carried out to test DVA on a 2 DoF milling machine [13]. The reduced vibration is directly proportional to the stability of the tool blade movement, making the milling results smoother, and the machine efficiency increases with the increase in the depth of cut of the machine.

This research study focuses on adding a Mass-Rubber Dynamic Vibration Absorber (MR-DVA) as a translational vibration reducer on a drilling machine in the y-axis direction. Simulations were conducted to determine the effect of the MR-DVA placement distance to the hole and to test the application of MR-DVA within the natural frequency range of the workpiece as the main system.

2. Methodology

This study referred to the parameters of the drilling machine from Kao Ming Machinery Industrial Co., Ltd., type KMR-700DS, with an engine speed of 441 rpm. The simulation used ANSYS 2021 R2 Student Version. The main system consisted of a drill bit and a workpiece. The workpiece material was Aluminium Alloy 7075-T6 with various dimension ratios. As shown in Figure 1 translational vibrations were only analyzed in the y-axis translational direction. In addition to various workpiece sizes, the study also varied the distance ratio between MR-DVA placement and the clamping of the drill hole, as shown in Figure 2.

This research used MR-DVA, which was composed of mass and stiffness. The mass ratio of MR-DVA was 1/20 from the main system in the form of a brass coin. The stiffness of MR-DVA came from natural rubber. Both brass coin and rubber had a diameter of 38 mm and a thickness of 5 mm. The motion of the MR-DVA was limited by the y-axis direction translation caused by a frame made out of acrylic.

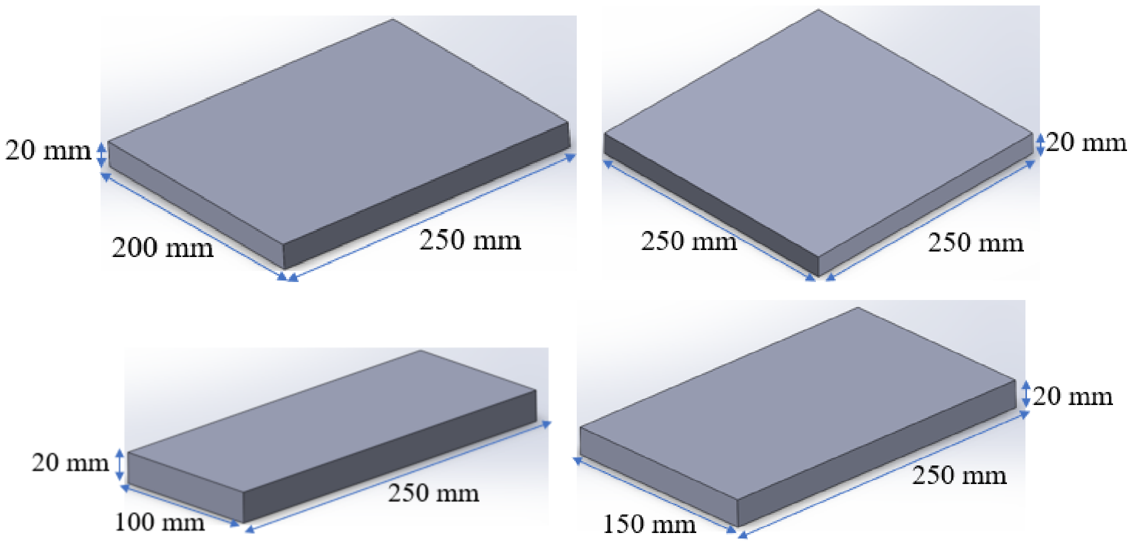


Figure 1. Workpieces size ratio variation.

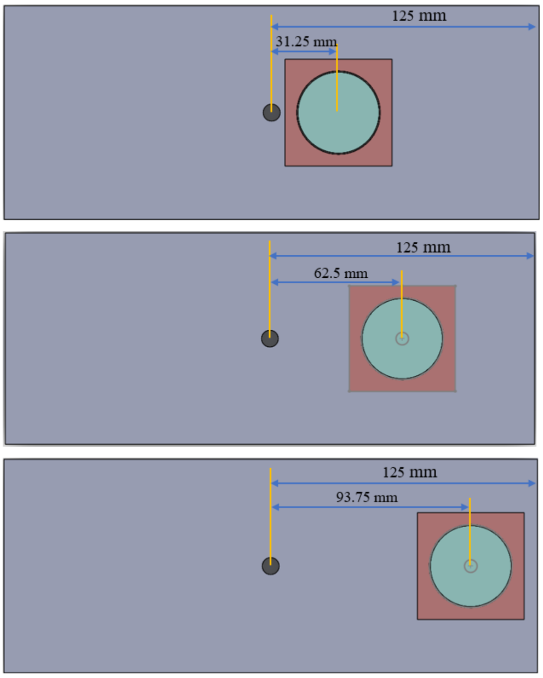


Figure 2. The distance ratio between MR-DVA placement and the clamping of the drill hole variation.

MR-DVA with a natural frequency of 1630.2 Hz was tested within the workpiece's natural frequency range to make it more applicable, which was 1675 Hz to 1680 Hz. The natural frequency of the MR-DVA was similar to the system's natural frequency, which avoided resonance. The mass ratio of 1⁄20 was the mass to main system ratio, which was the ideal ratio for DVA [14]. The natural rubber had Young's modulus, which made it work well in damping the vibration of the research system. From the design shown in Figure 3, the main system's dynamic model without MR-DVA was 1DoF, and the one with MR-DVA was 2DoF, as shown in Figure 4.

where M_1 was the workpiece mass, M_2 was the damper mass, c_1 was the damping constant of workpieces, c_2 was the damping constant of MR-DVA, k_1 was the stiffness of workpieces, k_2 was the stiffness of MR-DVA, $y_1(t)$ was the displacement of the workpiece for the y-axis, $y_2(t)$ was the displacement of MR-DVA for the y-axis, and $F(t)$ was the excitation force of the main system. Based on the dynamic system model of the workpiece with MR-DVA added in Figure 4, Equation 1 and 2 was obtained.

$$M_1\ddot{y}_1+(c_1+c_2)\dot{y}_1-c_2\dot{y}_2+(k_1+k_2)y_1-k_2y_2=F(t) \quad (1)$$

$$M_2\ddot{y}_2+c_2\dot{y}_2-c_2\dot{y}_1+k_2y_2-k_2y_1=0 \quad (2)$$

The translational force $F(t)$ of the drill-bit was affected by the thread toward the x and y axes, as shown in Figure 5. Therefore the excitation force was expressed as Equation 3:

$$\vec{F}=F_x+F_y \quad (3)$$

Excitation of drill-bit was a sinusoidal force with $Fe^{i\omega t}$, the displacement $y_1(t)$ was expressed as:

$$y_j(t)=Y_je^{i\omega t}; j=1,2$$

Where Y_j was the complex steady-state amplitude of the main system. By solving Equation 1, the analytic solution of complex steady-state amplitude was expressed as:

$$\frac{Y_1}{F/k_1}=\frac{(-M_2\omega^2+ic_2\omega+k_2)}{\begin{aligned}&\Big[\tfrac{M_1M_2\omega^4}{k_1}-(\tfrac{M_1k_2}{k_1}+M_2+\tfrac{M_2k_2}{k_1}-\tfrac{c_1c_2}{k_1})\omega^2\\&+k_2\Big]+i\Big[(-\tfrac{M_1c_2}{k_1}-\tfrac{M_2c_1}{k_1}-\tfrac{M_2c_2}{k_1})\omega^2r\\&+(-\tfrac{c_1k_2}{k_1}+c_2)\omega\Big]\end{aligned}} \quad (4)$$

By defining:

$$\Omega_n=\sqrt{k_1/M_1};\qquad \omega_n=\sqrt{k_2/M_2};\qquad \mu=M_1/M_2;$$
$$Z=\frac{c_1}{2M_1\Omega_n};\qquad \zeta=\frac{c_2}{2M_2\Omega_n}$$

From Equation 4, the real steady-state amplitude ratio of the main system with MR-DVA was obtained as Equation 5:

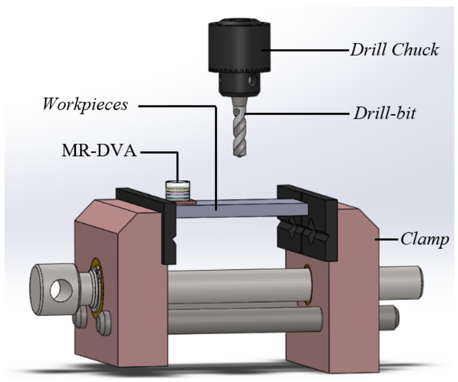
$$\frac{Y_1}{Y_{st}}=\sqrt{\frac{A^2+B^2}{C^2+D^2}} \quad (5)$$

where:

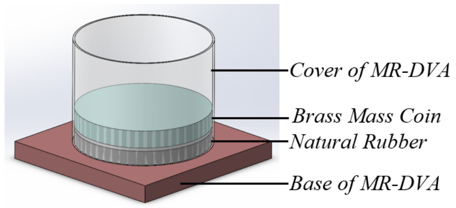
$$A=1-\left(\frac{\Omega_n}{\omega_n}\right)\left(\frac{\omega}{\Omega_n}\right)^2$$
$$B=2\zeta\left(\frac{\Omega_n}{\omega_n}\right)\left(\frac{\omega}{\Omega_n}\right)$$
$$C=\left(\frac{\Omega_n}{\omega_n}\right)^2\left(\frac{\omega}{\Omega_n}\right)^4 -\left(1+\frac{{\Omega_n}^2}{{\omega_n}^2}+\mu+4Z\zeta\left(\frac{\Omega_n}{\omega_n}\right)^2\right)\left(\frac{\omega}{\Omega_n}\right)^2+1$$
$$D=-\left(1+\frac{Z}{\zeta}\left(\frac{\Omega_n}{\omega_n}\right)+\mu\right)\left(\frac{\omega}{\Omega_n}\right)^2 +\left(\frac{Z}{\zeta}\left(\frac{\Omega_n}{\omega_n}\right)+1\right)\left(\frac{\Omega_n}{\omega_n}\right)\left(\frac{\omega}{\Omega_n}\right)$$

In this study, the cutting parameters of the drill machining process included an engine rotation speed of 441 rpm, feed speed of 0.13 mm/rev, and cutting speed of 100 m/min. The drill bit used was a straight shank model, as shown in Figure 5.

The analysis was at the chatter frequency of 1,686 Hz, obtained from the drilling process experiment, to see the vibration reduction response from the resulting hole surface. The research excitation force was the cutting parameter based on Table 1. Static deformation (K_{st}) obtained by using static structural analysis shown in Figure 6.

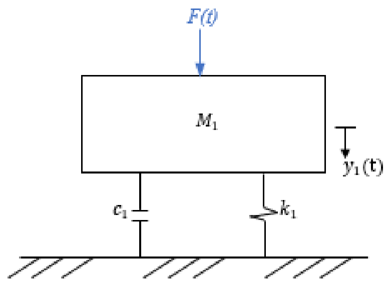


(a) Main system scheme.

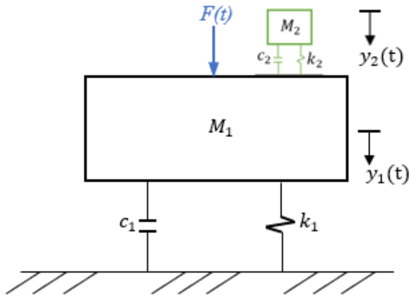


(b) Mass-rubber dynamic vibration absorber (MR-DVA).

Figure 3. Main system scheme and MR-DVA.



(a) without MR-DVA.



(b) with MR-DVA.

Figure 4. Dynamic model of main system.

Figure 5. Drill-bit.

Table 1. Cutting parameter of drill-bit.

Drill-bits ϕ (mm)	N (rpm)	F (mm/rev)	ω_c (Hz)	Force (N)	x-axis Force (N)	y-axis Force (N)
8	441	0.13	1686	276.67	259.98	94.62

The excitation force was used as input for the force boundary condition in the simulation with ANSYS 2021 R2 Student Version Workbench software. The direction of the excitation force followed the threads of the drill-bit in the x and y axes, while the fixed support represented the clamp grip on the vise.

The research parameters were obtained by simulating the system with Modal and Static Structural analysis of the simulation software. The value of the stiffness constant of the main system on the hole positioning was calculated using static structural simulation by providing the boundary condition. Concentrated force on the hole as a drill-bit representation of 276.67 N in a vertical direction (y-axis), as shown in Figure 7. The equivalent stiffness constant of the main system was calculated by the Equation 6.

$$k_1 = \frac{F}{k_{st}} \tag{6}$$

After the equivalent stiffness obtained by static structural analysis in Figure 7, modal simulation in Figure 8 was used to determine the equivalent mass by Equation 7.

$$M_1 = \frac{k_1}{\omega^2} \tag{7}$$

Table 2. Main system paremeter.

Workpieces Size Ratio	k_1 (N/m)	M_1 (kg)	c_1 (Ns/m)	ω_{n1} (Hz)	ζ_1
2/5	5.4×10^7	0.48	4.09	1675.5	0.0004
3/5	6.2×10^7	0.56	4.74	1677.6	0.0004
4/5	8.3×10^7	0.74	6.27	1687.3	0.0004
5/5	8.9×10^7	0.78	6.65	1696.6	0.0004

Table 3. MR-DVA parameter.

Rubber Type	Mass Ratio	k_2 (N/m)	M_2 (kg)	c_2 (Ns/m)	ω_{n2} (Hz)	ζ_2
Natural	1/20	148357.1621	0.00142	0.57965	1630.2	0.02

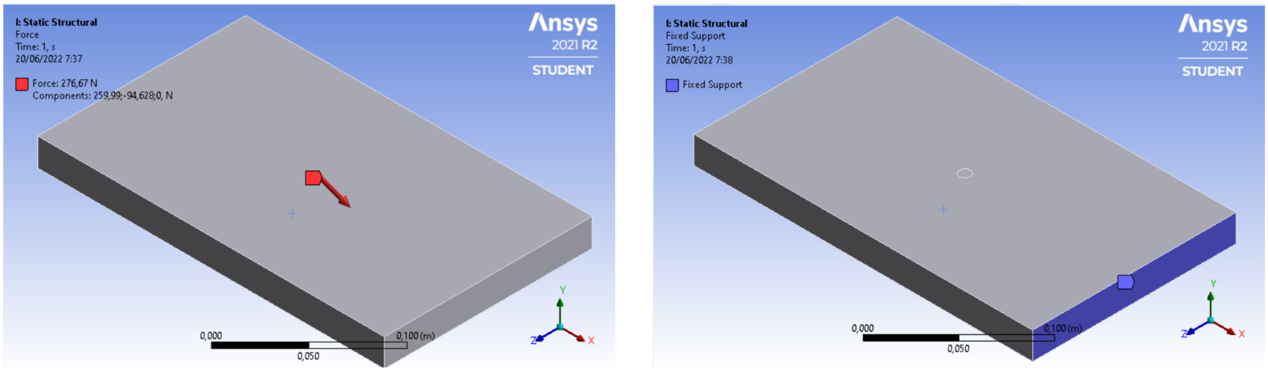


Figure 6. Workpieces size ratio variation.

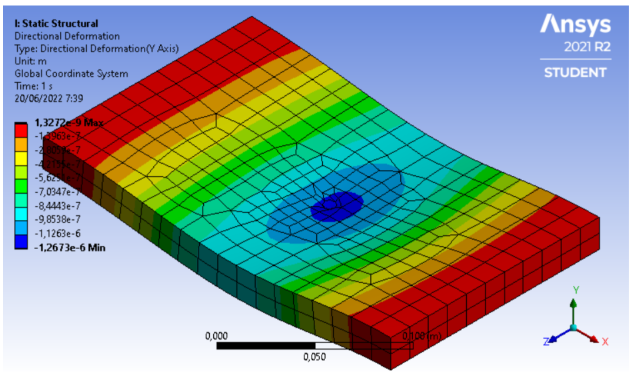


Figure 7. Static deformation simulation.

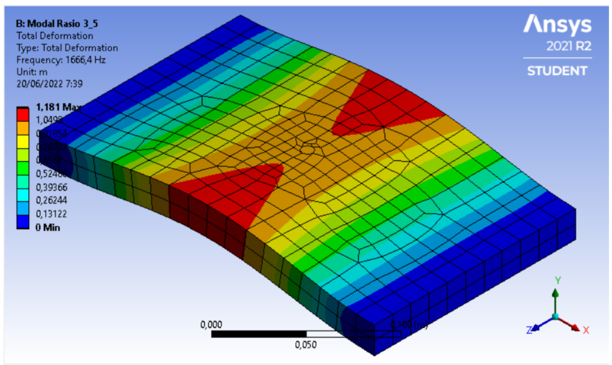


Figure 8. Natural frequency simulation.

Constant damping was obtained by using Equation 8, where the damping ratio (ζ_1) depended on the material of the workpieces, as shown in Table 2.

$$c_1 = 2\zeta_1 \sqrt{M_1 k_1} \tag{8}$$

The same process was conducted to obtain the MR-DVA parameter shown in Table 3.

The research was conducted by simulating related systems using the meshing method. Meshing was a finite element method as a geometric approach to the original form of the system. In this study, three simple meshing methods are used: face meshing, multizone, and automatic. The multizone was used on objects with a cylindrical shape to maintain the shape of the mesh with a hexahedral profile, such as on the MR-DVA frame, brass mass coins, and DVA rubber. For flat cube geometry, which is the workpiece and the frame base of the MR-DVA, an automatic mesh with an element size of 20 mm was used. For the force application, a face split as big as the diameter of the drill-bit required, which was 8 mm. Furthermore, the inflation and face meshing methods were applied to the surface of the workpiece that had drill holes. There were 27,054 nodes and 22,273 elements for the main system geometry with the addition of MR-DVA. Then, the minimum, maximum, and average element quality for orthogonal metric mesh was obtained, which was considered suitable for the excellent category on the orthogonal mesh metric spectrum, as shown in Figure 9.

Harmonic Response analysis in ANSYS 2021 R2 Student Version shown in Figure 10 was used in the y-axis direction to add MR-DVA to the system to determine the response of vibration reduction in the area around the hole. From this analysis, a Bode Diagram graph was obtained from the amplitude response of the main system to the solution frequency response deformation in the y-axis direction.

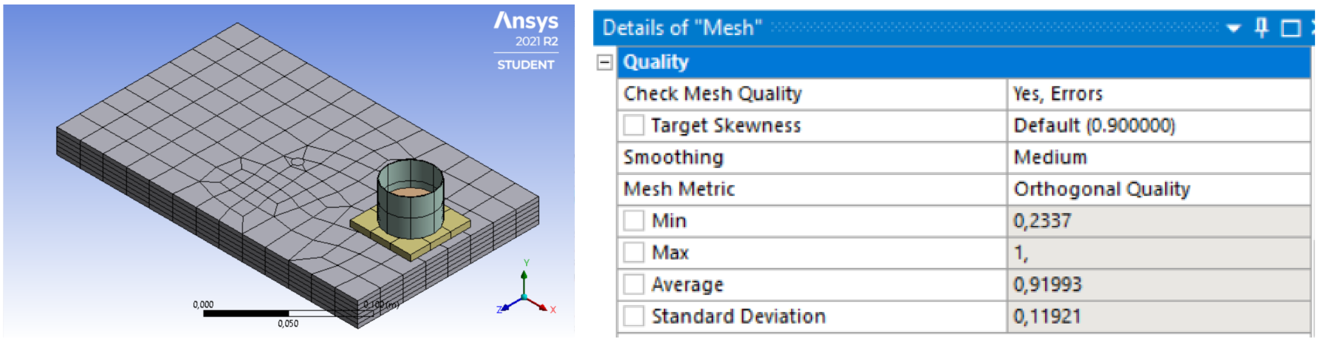


Figure 9. Mesh.

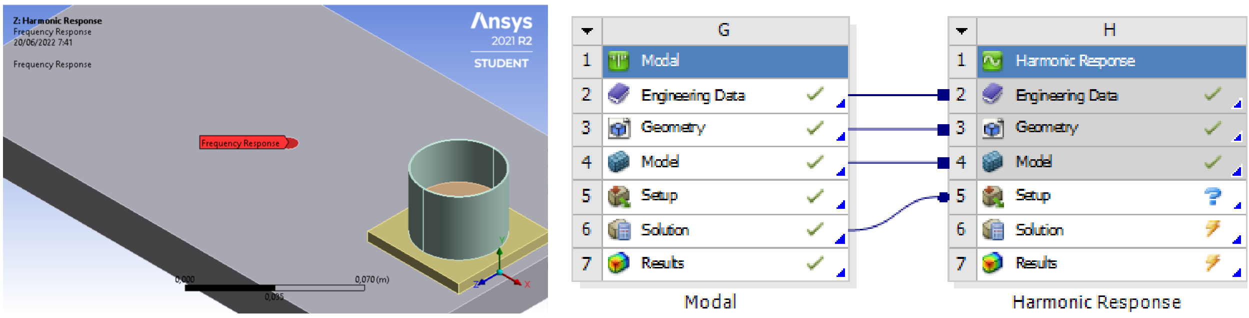


Figure 10. Harmonic response.

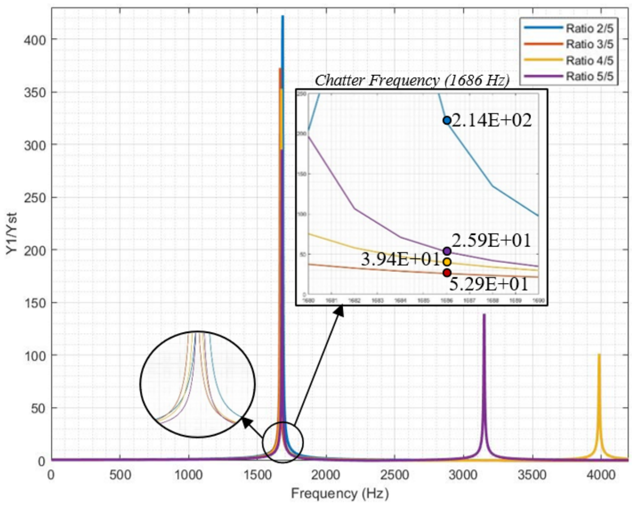


Figure 11. Various size ratio of main system bode diagram without MR-DVA.

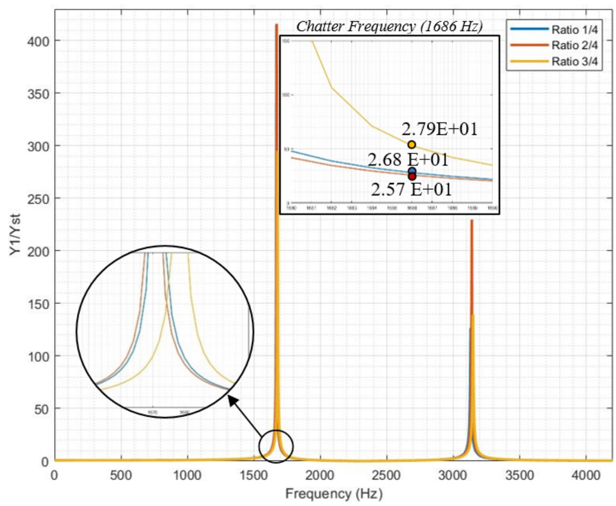


Figure 12. Various size ratio of main system bode diagram with MR-DVA.

3. Results and Discussion

In this simulation data retrieval, the data obtained is a translational vibration response output in the form of a frequency response of the hole area in the y-axis direction. The simulation data ranges from 2 to 4,200 Hz for each workpiece and is processed using Ms. Excel software. After that, the dynamic vibration response is divided by the static response as a normalization of the vibration amplitude to Y_1/Y_{st}. The dimensionless frequency response plotted in the MATLAB software. Simulations are conducted on the main system before and after adding a mass-rubber dynamic vibration absorber (MR-DVA) by varying the ratio of MR-DVA placement distance.

3.1. Analysis of Main System Vibration Response without the Addition of MR-DVA

The translational vibration response analysis of the main system is first conducted with four variations of the workpiece dimension ratio for the y-axis direction without the addition of MR-DVA. Figure 11 is the simulation output of the drilling process without adding MR-DVA in the form of a frequency responses diagram of each workpiece dimension variation. The frequency domain of the main system comes from vibrations in the area around the drill hole for translational vibrations in the y-axis direction, and the focus of this analysis is on the chatter frequency of 1,686 Hz, which is obtained from the impact hammer test. The result of the impact hammer test was then processed using the logarithmic decrement method.

The vibration amplitude response ratio in the main system with a dimension ratio of 2⁄5 produces the largest vibration. In contrast, the workpiece dimension ratio of 3⁄5 is the ratio of the workpiece dimension that produces the lowest vibration response. From the ratio of the workpiece dimensions 3⁄5, the vibration increased to the ratio of the workpiece dimensions 5⁄5. The peak in the Bode Diagram indicates the number of the main operating system DoF, which has one resonance point at the natural frequency of the workpiece. The highest amplitude value indicates this on the graph.

3.2. Main System Vibration Response Analysis with the Addition of MR-DVA to Variation of MR-DVA Placement Ratio

In this simulation, the distance of MR-DVA placement is varied by 1⁄4, 2⁄4, and 3⁄4 between the clamping distance against the drill hole. The analysis is carried out at the chatter frequency of 1,686 Hz resulting in a pattern in the form of a trendline bode diagram in Figure 12. It shows that the workpiece dimension ratio of 2⁄5 and 3⁄5 has the lowest vibration response with the MR-DVA placement distance ratio of 1⁄4, while the workpiece dimension ratio of 4⁄5 and 5⁄5 has the lowest vibration response when MR-DVA is placed as far as a distance ratio of 2⁄4. However, in the four variations of the workpiece dimension ratio, the highest amplitude ratio response is found when the MR-DVA was placed at the distance ratio of 3⁄4.

Making the short part wider increases vibration response. Interestingly, there is a slight difference in the phenomena that occur at the workpiece dimension ratio of 2⁄5 and 3⁄5. It is found that the amplitude ratio response increases as the variation of the smallest to largest MR-DVA placement ratio increases at the same time. In contrast, the workpiece dimension ratio of 4⁄5 and 5⁄5 tends to produce a decrease in vibration amplitude response from variations in the MR-DVA placement ratio of 1⁄4 to a placement distance ratio of 2⁄4 and then rises again to a placement ratio of 3⁄4. This is certainly caused by the resilience and rigidity of the workpiece.

3.3. Analysis of the Range between Peak and Valley against Dimension Ratio

The gap between a valley and peaks represents the system's muffled frequency range. Figure 13 shows a pattern made by various workpiece size ratios. In that case, to see this phenomenon in more detail, simulation data is taken to prove the analysis up to a frequency of 8500 Hz.

The second peak that appears with the closest and highest valley to the second furthest and the lowest peak is based on the workpiece dimension ratio of 5⁄5, 4⁄5, 3⁄5, and 2⁄5. This is in line with the equivalent stiffness value of the workpiece dimension ratio, where the higher the equivalent stiffness of the workpiece, the narrower the valley between the two peaks becomes. The valley mentioned is the length of the dampen frequency range for each size ratio. This is in accordance with the results obtained [8].

3.4. Vibration Reduction Analysis of MR-DVA Placement Variations on Drill Holes

The frequency response diagram below was obtained with workpieces of 2/5 as size ratio before and after the addition of MR-DVA. At the chatter frequency of 1,686 Hz, there is a reduction in vibration, which is indicated by a green line (the main system without MR-DVA) which is exactly on the main system with a ratio of 3⁄4 MR-DVA placement yellow line, while red is the ratio of MR-DVA placement of 2/4, and the blue line belongs to the MR-DVA placement ratio of 1/4, as shown in Figure 14.

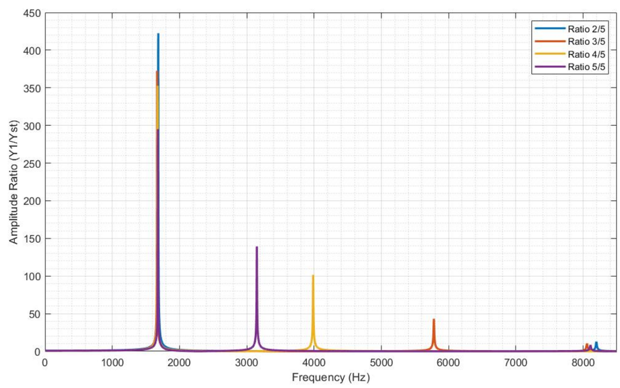


Figure 13. Bode diagram phenomenon.

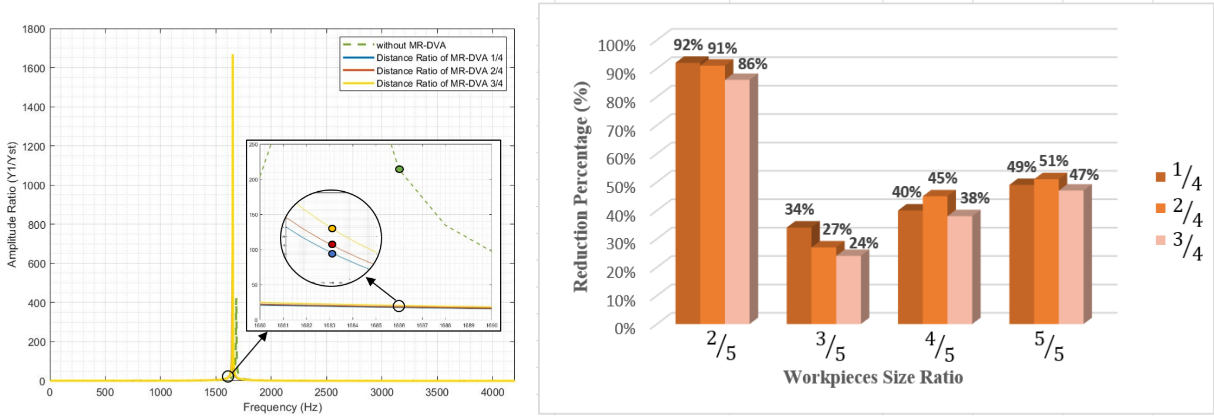


Figure 14. Harmonic response.

According to the graph shown in Figure 14, the appropriateness of the system from the MR-DVA design where the MR-DVA that can absorb the most maximum is the MR-DVA mass ratio of 1⁄20 [12]. This MR-DVA design is the most optimal for damping the main system with a workpiece dimension ratio of 2⁄5, as shown in the bar chart above, while the percentage reduction produced can reach up to 92% for an MR-DVA placement ratio of 1⁄4. In comparison, the lowest reduction is found in the workpiece dimension ratio of 3⁄5 for each variation of the MR-DVA placement ratio. The workpiece dimension ratios that produce the highest to the lowest percentage reduction in amplitude response ratio are 2⁄5, 5⁄5, 4⁄5, and 3⁄5.

Based on this research analysis, the results are indicated by adding the DVA types Mass-Rubber makes a shift in the natural frequency location close to the excitation frequency range in the system. Variations of the dimension ratio of workpieces and placement of MR-DVA also played along in determining the maximum parameter needed.

4. Conclusion

As a result of the simulation, the optimal reduction of the workpiece dimension ratio damping area of 2⁄5 and 3⁄5 occurs when the MR-DVA placement ratio is 1⁄4. Meanwhile, at the workpiece dimension ratio of 4⁄5 and 5⁄5, the optimal reduction occurs when the MR-DVA placement ratio is 2⁄4, proved by the second peak with a narrower damping area. The biggest reduction is in the workpiece dimension ratio of 2/5, with the 1⁄4 MR-DVA placement ratio at 92%. In contrast, the lowest reduction is found in the workpiece dimension ratio of 3/5, with the 1/4 MR-DVA placement ratio at 24%.

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